

New mechanism of generation of large-scale magnetic fields in merging protogalactic and protostellar clouds

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Abstract. A new mechanism of generation of large-scale magnetic fields in colliding protogalactic clouds and merging protostellar clouds is discussed. Interaction of the colliding clouds produces large-scale shear motions which are superimposed on small-scale turbulence. Generation of the large-scale magnetic field is due to a "shear-current" effect (or "vorticity-current" effect), and the mean vorticity is caused by the large-scale shear motions of colliding clouds. This effect causes the generation of the mean magnetic field even in a nonrotating and nonhelical homogeneous turbulence. There is no quenching of the nonlinear shear-current effect contrary to the quenching of the nonlinear alpha effect, the nonlinear turbulent magnetic diffusion, etc. During the nonlinear growth of the mean magnetic field, the shear-current effect only changes its sign at some value of the mean magnetic field which determines the level of the saturated mean magnetic field. Numerical study shows that the saturated level of the mean magnetic field is of the order of the equipartition field determined by the turbulent kinetic energy. The estimated large-scale magnetic field for merging protogalactic clouds is about several microgauss, and for merging protostellar clouds is of the order of several tenth of microgauss.

Key words: Magnetic fields – turbulence – MHD

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1. Introduction

The generation of magnetic fields in astrophysical objects, e.g., galaxies, stars, planets, is one of the outstanding problems of physics and astrophysics. The initial seed magnetic fields of galaxies and stars are very weak, and are amplified by the dynamo process. The generated magnetic field is saturated due to nonlinear effects.

The origin of seed magnetic fields in the early Universe, e.g., at phase transitions, is a subject of discussions. However, the merging of such seed magnetic fields, hardly could produce a substantial large-scale magnetic fields observed at the present time (Peebles 1980; Zeldovich & Novikov 1983). The origin of seed magnetic fields in self-gravitating protogalactic clouds was studied by Birk et al. (2002) (see also Wiechen et al. 1998). It was suggested that the seed magnetization of protogalaxies can be provided by relative shear flows and collisional friction of the ionized and the neutral components in partially ionized self-gravitating and rotating protogalactic clouds. Self-consistent plasma-neutral gas simulations by Birk et al. (2002) have shown that seed mag-

netic fields $\sim 10^{-14}$ G arise in self-gravitating protogalactic clouds on spatial scales of 100 pc during 7×10^6 years.

In this paper we discuss a new mechanism of generation of large-scale magnetic fields in colliding protogalactic and merging protostellar clouds. Interaction of the merging clouds causes large-scale shear motions which are superimposed on small-scale turbulence. Generation of the large-scale magnetic field is caused by a "shear-current" effect or "vorticity-current" effect (Rogachevskii & Kleeorin 2003; 2004). The mean vorticity is produced by the large-scale shear motions of colliding protogalactic and merging protostellar clouds (Chernin et al. 1991; 1993).

Let us first discuss a scenario of formation the large-scale shear motions in colliding protogalactic clouds. Jean's process of gravitational instability and fragmentation can cause a very clumsy state of cosmic matter at the epoch of galaxy formation. A complex system of rapidly moving gaseous fragments embedded into rare gas might appear in some regions of protogalactic matter. Supersonic contact collisions of these protogalactic clouds might play a role of an important elementary process in a complex nonlinear dynamics of protogalactic medium. The supersonic contact non-central col-

lisions of these protogalactic clouds could lead to their coalescence, formation of shear motions and transformation of their initial orbital momentum into the spin momentum of the merged condensations bound by its condensations (Chernin 1993).

Two-dimensional hydrodynamical models for inelastic non-central cloud-cloud collisions in the protogalactic medium have been developed by Chernin (1993). An evolutionary picture of the collision is as follows. At the first stage of the process the standard dynamical structure, i.e., two shock fronts and tangential discontinuity between them arise in the collision zone. Compression and heating of gas which crosses the shock fronts occurs. The heating entails intensive radiation emission and considerable energy loss by the system which promotes gravitational binding of the cloud material. At the second stage of the process a dense core forms at the central part of the clump. In the vicinity of the core two kinds of jets form: "flyaway" jets of the material (which does not undergo the direct contact collision) and internal jets sliding along the curved surface of the tangential discontinuity. The flyaway jets are subsequently torn off, having overcome the gravitational attraction of the clump whereas the internal jets remain bound in the clump. When the shock fronts reach the outer boundaries of the clump, the third stage of the process starts. Shocks are replaced by the rarefaction waves and overall differential rotation and large-scale shear motions arise. This structure can be considered as a model of the protogalactic condensation (Chernin 1993). The formed large-scale sheared motions are superimposed on small-scale turbulence.

There are two important characteristics of the protogalactic cloud - cloud collisions: the mass bound in the resulting clump and the spin momentum acquired by it. These characteristics depend on the relative velocity and impact parameter of the collision (Chernin 1993). The parameters of a protogalactic cloud are following: the mass is $M \leq 10^{10} M_{\odot}$, the radius is $R \sim 10^{23}$ cm, the internal temperature is $T \sim 10^4$ K, the mean velocity of the cloud is $V \sim 10^6 - 10^7$ cm/s, where M_{\odot} is the solar mass. Some other parameters for the protogalactic clouds (PGC) are given in Table 1 in Section 3.

An important feature of the dynamics of the interstellar matter is fairly rapid motions of relatively dense matter fragments (protostellar clouds) embedded in to rare gas. The origin of protostellar clouds might be a result of fragmentation of the core of large molecular clouds. Supersonic and inelastic collisions of the protostellar clouds can cause merging of the clouds and formation of a condensation. A non-central collision of the protostellar clouds can cause conversion of initial orbital momentum of the clouds in to spin momentum and formation of differential rotation and shear motions (Chernin 1991). The internal part of the condensation would have only slow rotation because the initial matter motions could be almost stopped in the zone of direct cloud contact. On the other hand, the minor outer part of the merged cloud matter of the condensation would have very rapid rotation due to the initial motions of that portions of cloud materials which would not stop in this zone because they do not undergo any direct cloud collision (Chernin 1991). This ma-

terial could keep its motion on gravitationally bound orbits around the major internal body condensation. The formed large-scale sheared motions are superimposed on small-scale interstellar turbulence.

In the supersonic and inelastic collision of the protostellar clouds an essential part of the initial kinetic energy of the cloud motions will be lost with the mass lost and also due to dissipation and subsequent radiative emission. The cooling time scale for the material compressed in the collision would be less than the time scale of the hydrodynamic processes. An estimate of basic physical quantities which characterize the above processes has been made by Chernin (1991). Thus, e.g., the parameters of a protostellar cloud are as follows: a mass is $M \leq M_{\odot}$, the radius is $R \sim 10^{17}$ cm, the internal temperature is $T \sim 10$ K, the mean velocity of the cloud is $V \sim 10^5 - 10^6$ cm/s. Some other parameters for the protostellar clouds (PSC) are given in Table 1 in Section 3.

2. Generation of large-scale magnetic field due to the shear-current effect

Now we discuss generation of large-scale magnetic field due to the shear-current effect. We suggested that this effect is responsible for the large-scale magnetic fields in colliding protogalactic clouds and merging protostellar clouds.

The large-scale magnetic field can be generated in a helical rotating turbulence due to the α effect. When the rotation is a nonuniform, the generation of the mean magnetic field is caused by the $\alpha\Omega$ dynamo. For a nonrotating and nonhelical turbulence the α effect vanishes. However, the large-scale magnetic field can be generated in a nonrotating and nonhelical turbulence with an imposed mean velocity shear due to the shear-current effect (see Rogachevskii & Kleeorin 2003; 2004). This effect is associated with the $\delta \times \mathbf{J}$ term in the mean electromotive force, where \mathbf{J} is the mean electric current. In order to elucidate the physics of the shear-current effect, we compare the α effect in the $\alpha\Omega$ dynamo with the $\delta \times \mathbf{J}$ term caused by the shear-current effect. The α term in the mean electromotive force which is responsible for the generation of the mean magnetic field, reads $\mathcal{E}^{\alpha} \equiv \alpha \mathbf{B} \propto -(\boldsymbol{\Omega} \cdot \boldsymbol{\Lambda}) \mathbf{B}$ (see, e.g., Krause & Rädler 1980; Rädler et al. 2003), where $\boldsymbol{\Lambda} = \nabla \langle \mathbf{u}^2 \rangle / \langle \mathbf{u}^2 \rangle$ determines the inhomogeneity of the turbulence. The $\delta \times \mathbf{J}$ term in the electromotive force caused by the shear-current effect is given by $\mathcal{E}^{\delta} \equiv -\delta \times (\nabla \times \mathbf{B}) \propto (\mathbf{W} \cdot \nabla) \mathbf{B}$, where δ is proportional to the mean vorticity $\mathbf{W} = \nabla \times \mathbf{U}$ caused by the mean velocity shear (Rogachevskii & Kleeorin 2003; 2004).

The mean vorticity \mathbf{W} in the shear-current dynamo plays a role of a differential rotation and an inhomogeneity of the mean magnetic field plays a role of the inhomogeneity of turbulence. During the generation of the mean magnetic field in both cases (in the $\alpha\Omega$ dynamo and in the shear-current dynamo), the mean electric current along the original mean magnetic field arises. The α effect is related to the hydrodynamic helicity $\propto (\boldsymbol{\Omega} \cdot \boldsymbol{\Lambda})$ in an inhomogeneous turbulence. The deformations of the magnetic field lines are caused by upward and downward rotating turbulent eddies in the $\alpha\Omega$ dynamo. Since the turbulence is inhomogeneous (which

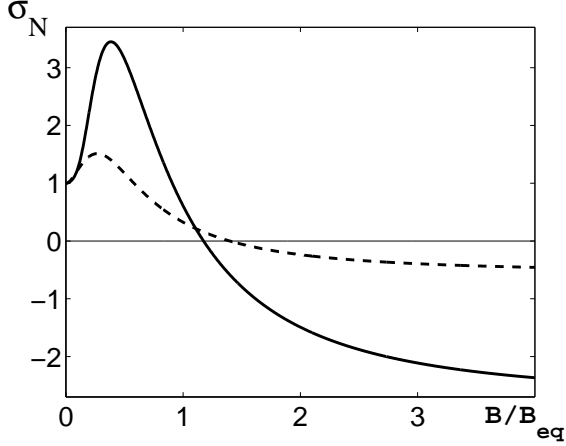


Fig. 1. The dimensionless nonlinear coefficient $\sigma_N(B)$ defining the shear-current effect for different values of the parameter ϵ : $\epsilon = 0$ (solid); $\epsilon = 1$ (dashed).

breaks a symmetry between the upward and downward eddies), their total effect on the mean magnetic field does not vanish and it creates the mean electric current along the original mean magnetic field.

In a turbulent flow with an imposed mean velocity shear, the inhomogeneity of the original mean magnetic field breaks a symmetry between the influence of upward and downward turbulent eddies on the mean magnetic field. The deformations of the magnetic field lines in the shear-current dynamo are caused by upward and downward turbulent eddies which result in the mean electric current along the mean magnetic field and produce the magnetic dynamo.

Let us consider for simplicity a homogeneous turbulence with a mean linear velocity shear, i.e., the mean velocity $\mathbf{U} = (0, Sx, 0)$ and the mean vorticity $\mathbf{W} = (0, 0, S)$. The mean magnetic field, $\mathbf{B} = B(x, z) \mathbf{e}_y + (D/S_*) \nabla \times [A(x, z) \mathbf{e}_y]$, is determined by the dimensionless dynamo equations

$$\frac{\partial A}{\partial t} = \sigma_N(B) \nabla_z B + \Delta A, \quad (1)$$

$$\frac{\partial B}{\partial t} = -D \nabla_z A + \Delta B, \quad (2)$$

(Rogachevskii & Kleeorin 2003; 2004), where $D = (l_0/L)^2 S_*^2 \sigma_0$ is the dynamo number, $S_* = SL^2/\eta_T$ is the dimensionless shear number, $\sigma_0 = (4/135)(1 + 9\epsilon)$, the parameter ϵ is the ratio of the magnetic and kinetic energies in the background turbulence (i.e., turbulence with a zero mean magnetic field), L is the characteristic scale of the mean magnetic field variations, η_T is the turbulent magnetic diffusivity, $\sigma_N(B)$ is the function defining nonlinear shear-current effect which is normalized by σ_0 . We adopted here the dimensionless form of the mean dynamo equations; in particular, length is measured in units of L , time is measured in units of L^2/η_T and \mathbf{B} is measured in units of the equipartition energy $B_{\text{eq}} = \sqrt{4\pi\rho} u_0$, the turbulent magnetic diffusion coefficients are measured in units of the characteristic value of the turbulent magnetic diffusivity $\eta_T = l_0 u_0/3$, where u_0 is the characteristic turbulent velocity in the maximum scale of turbulent motions l_0 . In Eqs. (1) and (2) we have not taken into account a quenching of the turbulent magnetic diffusion.

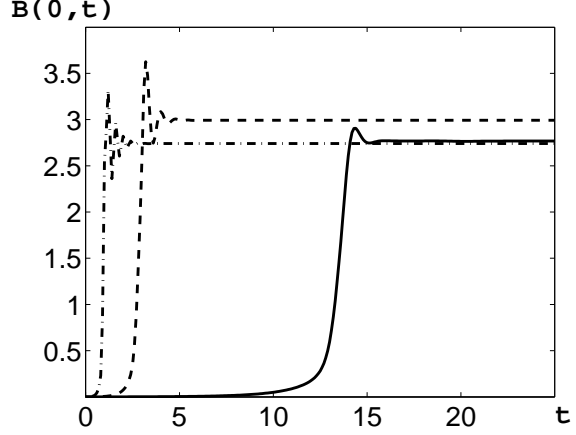


Fig. 2. The nonlinear evolution of the mean magnetic field $B(t, z = 0)$ due to the shear-current effect for $\epsilon = 0$ and different values of the dynamo number: $D = \pi^2/4 + 1$ (solid); $D = 10$ (dashed); $D = 40$ (dashed-dotted).

This facet is discussed in details by Rogachevskii and Kleeorin (2004).

The nonlinear function $\sigma_N(B)$ defining the shear-current effect for a weak mean magnetic field $B \ll B_{\text{eq}}/4$ is given by $\sigma_N(B) = 1$, and for $B \gg B_{\text{eq}}/4$ it is given by $\sigma_N(B) = -11(1 + \epsilon)/4(1 + 9\epsilon)$. The function $\sigma_N(B)$ is shown in Fig. 1 for different values of the parameter ϵ . The nonlinear function $\sigma_N(B)$ changes its sign at some value of the mean magnetic field $B = B_*$. For instance, $B_* = 1.2B_{\text{eq}}$ for $\epsilon = 0$, and $B_* = 1.4B_{\text{eq}}$ for $\epsilon = 1$. The magnitude B_* determines the level of the saturated mean magnetic field during its nonlinear evolution.

Solution of Eqs. (1) and (2) for the kinematic problem we seek for in the form $\propto \exp(\gamma t + iK_z z)$, where

$$B_y(t, z) = B_0 \exp(\gamma t) \cos(K_z z), \quad (3)$$

$$B_x(t, z) = \frac{l_0}{L} \sqrt{\sigma_0} B_0 K_z \exp(\gamma t) \cos(K_z z), \quad (4)$$

and we considered for simplicity the case when the mean magnetic field \mathbf{B} is independent of x . The growth rate of the mean magnetic field is $\gamma = \sqrt{D} K_z - K_z^2$. The wave vector K_z is measured in units of L^{-1} and the growth rate γ is measured in η_T/L^2 . Consider the simple boundary conditions for a layer of the thickness $2L$ in the z direction, $B(t, |z| = 1) = 0$ and $A'(t, |z| = 1) = 0$, i.e., $\mathbf{B}(t, |z| = 1) = 0$, where A' is the derivative with respect to z . The mean magnetic field is generated when $D > D_{\text{cr}} = \pi^2/4$, which corresponds to $K_z = \pi/2$. Numerical solution of Eqs. (1) and (2) with these boundary conditions for the nonlinear problem is plotted in Fig. 2. In particular, Fig. 2 shows the nonlinear evolution of the mean magnetic field $B(t, z = 0)$ due to the shear-current effect for $\epsilon = 0$ and different values of the dynamo number D . Here $B(t, z = 0)$ is measured in units of the equipartition energy $B_{\text{eq}} = \sqrt{4\pi\rho} u_0$.

The shear-current effect was studied for large hydrodynamic and magnetic Reynolds numbers using two different methods: the spectral τ approximation (the third-order closure procedure) and the stochastic calculus, i.e., the

Feynman-Kac path integral representation of the solution of the induction equation and Cameron-Martin-Girsanov theorem (Rogachevskii & Kleeorin 2003; 2004). Note that recent studies by Rädler & Stepanov (2006) and Rüdiger & Kichatinov (2006) have not found the dynamo action in nonrotating and nonhelical shear flows using the second order correlation approximation (SOCA). This approximation is valid for small hydrodynamic Reynolds numbers. Indeed, even in a highly conductivity limit (large magnetic Reynolds numbers) SOCA can be valid only for small Strouhal numbers, while for large hydrodynamic Reynolds numbers (fully developed turbulence) the Strouhal number is unity.

Generation of the large-scale magnetic field in a nonhelical turbulence with an imposed mean velocity shear was recently investigated by Brandenburg (2005) and Brandenburg et al. (2005) using direct numerical simulations. The numerical results are in a good agreement with the theoretical predictions by Rogachevskii & Kleeorin (2004).

3. Discussion

In this paper we discussed a new mechanism of generation of the large-scale magnetic fields in colliding protogalactic and merging protostellar clouds. Interaction of the merging clouds produces large-scale shear motions which are superimposed on small-scale turbulence. The scenario of the mean magnetic field evolution is as follows. In the kinematic stage, the mean magnetic field grows due to the shear-current effect from a very small seed magnetic field. During the nonlinear growth of the mean magnetic field, the shear-current effect changes its sign at some value B_* of the mean magnetic field. The magnitude B_* determines the level of the saturated mean magnetic field. Since the shear-current effect is not quenched, it might be the only surviving effect, and this effect can explain the dynamics of large-scale magnetic fields in astrophysical objects with large-scale sheared motions which are superimposed on small-scale turbulence.

Note that the magnetic part of the α effect caused by the magnetic helicity is not zero even in nonhelical turbulence. It is a purely nonlinear effect. In this study we concentrated on the nonlinear shear-current effect and do not discuss the effect of magnetic helicity on the nonlinear saturation of the mean magnetic field (see, e.g., Kleeorin et al. 2000, 2002; Blackman & Brandenburg 2002; Brandenburg & Subramanian 2005). This is a subject of a separate ongoing study.

In Table 1 we presented typical parameters of flow and generated magnetic fields in colliding protogalactic clouds (PGC) and merging protostellar clouds (PSC). We use the following notations: ΔV is the relative mean velocity, ΔR is the scale of the mean velocity inhomogeneity, $S = \Delta V / \Delta R$ is the mean velocity shear, u_0 is the characteristic turbulent velocity, l_0 is the maximum scale of turbulent motions, $\tau_0 = l_0 / u_0$ is the characteristic turbulent time, η_T is the turbulent magnetic diffusivity, $t_\eta = (\Delta R)^2 / \eta_T$ is the turbulent diffusion time, $B_{eq} = \sqrt{4\pi\rho} u_0$ is the equipartition large-scale magnetic field. Therefore, the estimated saturated large-scale magnetic field for merging protogalactic clouds is about

Table 1
The parameters of clouds

	PGC	PSC
Mass	$M \leq 10^{10} M_\odot$	$M \leq M_\odot$
R (cm)	$R \sim 10^{23}$	$R \sim 10^{17}$
V (cm/s)	$10^6 - 10^7$	$10^5 - 10^6$
ρ (g/cm ³)	10^{-26}	$(1 - 5) \times 10^{-19}$
ΔV (cm/s)	$10^6 - 10^7$	10^5
ΔR (cm)	2×10^{23}	$10^{16} - 10^{17}$
S (s ⁻¹)	$(0.5 - 5) \times 10^{-16}$	$10^{-12} - 10^{-11}$
u_0 (cm/s)	$10^6 - 10^7$	10^4
l_0 (cm)	10^{22}	$10^{15} - 10^{16}$
τ_0 (years)	$(0.3 - 3) \times 10^8$	$(0.3 - 3) \times 10^4$
η_T (cm ² /s)	$(0.3 - 3) \times 10^{28}$	$(0.3 - 3) \times 10^{19}$
t_η (years)	$(0.3 - 3) \times 10^9$	$10^6 - 10^7$
B_{eq} (μ G)	0.3 - 3	10 - 75

several microgauss, and for merging protostellar clouds is of the order of several tenth of microgauss (see Table 1).

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